High-speed visualization of erosion phenomena of tungsten-based electrode in multiphase AC arc

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Abstract: Evaporation phenomena from tungsten electrode with lanthanum oxide in multiphase AC arc were successfully visualized by high-speed camera. Results of synchronized visualization for tungsten and lanthanum vapour indicates that the evaporation of lanthanum triggers tungsten evaporation. Addition of the lanthanum vapour into the arc leads to higher electrical conductivity of the arc. Therefore, heat flux from the arc to the electrode become larger after the evaporation of lanthanum, resulting in tungsten evaporation.

Keywords: thermal plasmas, multiphase AC arc, electrode evaporation

1. Introduction

Thermal plasmas as an energy source with high energy efficiency have been applied in various engineering fields. They have various advantages such as extremely high temperature, high enthalpy to enhance reaction kinetics, rapid quenching capability to produce chemical non-equilibrium materials, and oxidation or reduction atmosphere in accordance with required chemical reaction. Therefore, these advances increase demands in plasma chemistry and plasma processing [1-3].

Multiphase AC arc is one of the thermal plasma generation systems. It is generated among multi-electrodes by phase-shifted AC power supplies. It has high energy efficiency because of the generation without converting AC to DC. It has various advantages such as large plasma volume and low gas velocity compared with the conventional thermal plasmas [4-6]. The multiphase AC arc is expected to be applied to massive powder processing such as nanomaterial fabrication processes and in-flight glass melting technology. However, fundamental phenomena have rarely been reported because of its novelty. In particular, electrode erosion is one of the most important issues to be solved because it determines the electrode lifetime and the purity of the products.

Tungsten electrode with doped oxide is generally used because of their suitable characteristics for stable arc operation. Doped oxide strongly influences electrode temperature and erosion rate because doped oxide reduces effective work function of the electrode [7]. In the multiphase AC arc, the erosion of tungsten electrode due to evaporation and droplet ejection was observed [8, 9]. In previous work, influence of doped oxide on the droplet ejection has been clarified. Doped oxide has an effect on the molten area of the electrode tip. Forces on the electrode tip are affected by doped oxide. As a result, the rate of erosion due to droplet ejection with an oxide doped electrode is smaller than that with a pure tungsten electrode. On the other hand, influence of doped oxide on the tungsten evaporation has not been understood yet. The purpose of this work is to investigate the evaporation mechanism of tungsten electrode with doped oxide in the multiphase AC arc. Dynamic behaviour of metal vapour from tungsten and doped oxide during AC cycle were visualized by high-speed camera system.

2. Experimental details

2.1 Experimental setup

Figure 1 shows a schematic image of the experimental setup. It consisted of 12 electrodes, arc chamber, and AC power supply at 60Hz. The electrodes were divided into two layers, upper six and lower six electrodes. The electrodes were symmetrically arranged by the angle of 30 degrees. The electrodes were made of tungsten (98wt%) and lanthanum oxide (2wt%) with diameter of 6.0 mm. To prevent the electrodes from oxidation, argon was injected around the electrode as shield gas at 2 L/min. The applied voltage between each electrode and the neutral point of the coil of the transformer can be calculated by the following equation:

$$V_i = V_m sin\left[\omega t - \frac{2\pi(i-1)}{12}\right] \quad (i = 1, 2, \dots, 12) \qquad (1)$$

where V_i indicates the applied non-load voltage for each electrode number i and V_m indicates the amplitude of the non-load voltage (about 220 V, AC 60Hz).

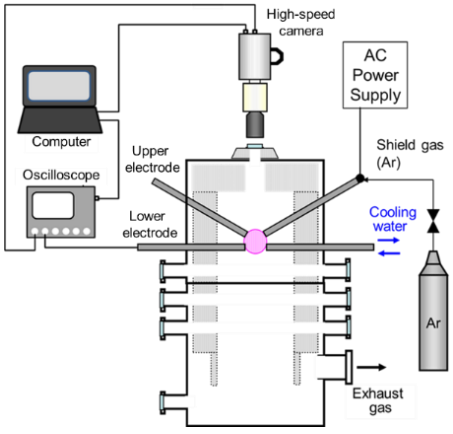

Fig. 1. Schematic image of multiphase AC arc generator.

The arc current was changed from 80 to 120 A for each electrode. Higher arc current leads to higher electrode temperature because higher heat flux to the electrode from the arc. Therefore, arc current was expected to influence on the electrode evaporation.

2.2 High-speed visualization of metal vapour

Evaporation of tungsten electrode was visualized by the high-speed camera system (FASTCAM SA-5, Photron Ltd., Japan). One of the electrodes was observed by high-speed camera installed on the top of the arc generator. Conventional observation of electrode during arc discharge was prevented by the strong emission of the arc. Therefore, the band-pass filter (Andover Optical Inc., USA) was combined with the high-speed camera system to separate the emission of metal vapour from the emission of the arc.

Schematic diagram of the high-speed camera system is shown in Fig. 2. The light focused by a lens of high-speed camera is divided into two optical paths by a splitter. In both paths, a band-pass filter in different wavelengths is placed for synchronized observation of the emissions from tungsten and lanthanum vapour. The appropriate wavelengths for the observation were determined based on spectroscopic measurements (iHR550, Horiba Jobin Yvon).

3. Results and discussion

3.1 High-speed visualization of tungsten vapour

Dynamic behaviour of tungsten vapour during an AC cycle was visualized by the high-speed camera system. Figure 3 shows the representative emission spectra at a distance of 2 mm from the electrode tip. Line emissions from tungsten vapour, as well as that from the oxygen atoms can be observed. As a result, centre wavelength of the band-pass filter was selected as 393 nm to separate the emission of tungsten vapour from the emission of the arc.

Figure 4 shows representatives of high-speed snapshots of the tungsten vapour with different arc current from 1.0 to 4.5 ms during an AC cycle. The indicated times in Fig. 4 (a), (b), (c) correspond to the waveform of arc current in Fig. 4 (d). In the multiphase AC arc, the evaporation of the tungsten electrode mainly observed at the anodic period. This is because tungsten ions near the electrode tip return

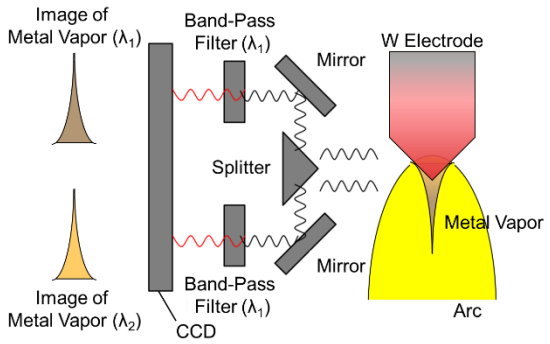

Fig. 2. Schematic diagram of high-speed camera system with band-pass filters.

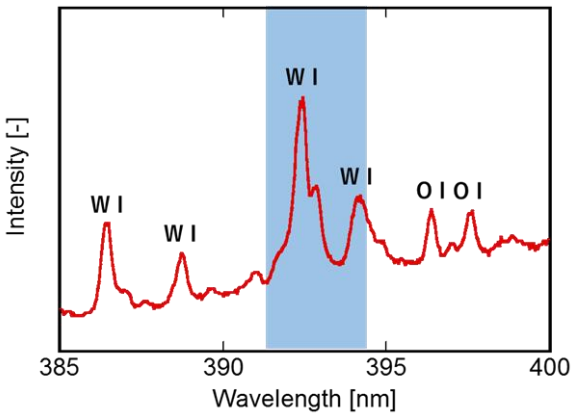

Fig. 3. Emission spectrum of multiphase arc in electrode region at centre wavelength of 393 nm.

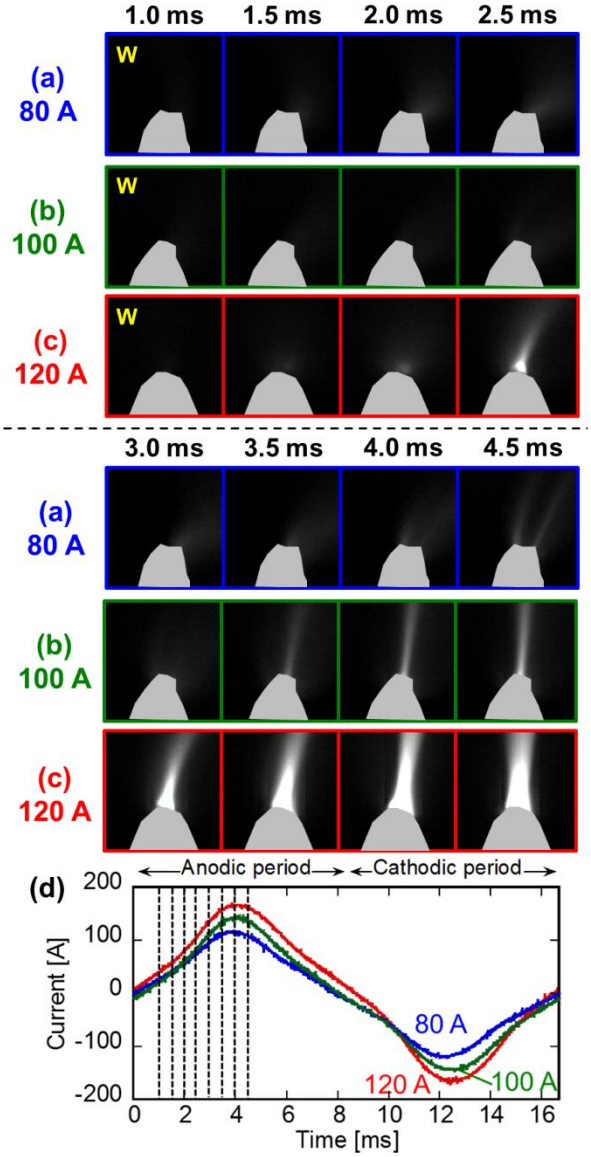

Fig. 4. High-speed snapshots of W vapour of La_2O_3-W at 80 (a), 100 (b), 120 A (c), and synchronized current waveform (d).

back to the electrode side due to electric field during the cathodic period.

According to the high-speed observation, luminance area of the tungsten vapour and timing when tungsten started to evaporate were influenced by values of the arc current. Higher arc current leads to severer evaporation of tungsten. Moreover, higher arc current leads to earlier evaporation timing. Tungsten evaporation at 120 A started before the peak top of the arc current at the anodic period. At 120 A, tungsten vapour observed at 2.5 ms as shown in Fig. 4 (c). In contrast, tungsten evaporation at 80 A and 100 A started near the peak top of arc current. At 80 A and 100 A, tungsten vapour observed at 3.5 ms and 4.0 ms as shown in Fig. 4 (a), (b).

Time variation of luminance area of the tungsten vapour during an AC cycle with different values of arc current are shown in Fig. 5. Results indicated that the area of tungsten vapour at 100 A was about 1.5 times larger than that at 80 A. Moreover, the area of tungsten vapour at 120 A was about 4 times larger than that at 100 A. To investigate the reason for severer evaporation of tungsten at 120 A, the evaporation timing with different values of arc current will be discussed in the following section.

3.2 High-speed visualization of vapour from doped oxide

Metal vapour from tungsten and doped oxide simultaneously observed by high-speed camera system. Figure 6 shows the representative emission spectra at a distance of 2 mm from the electrode tip. The band-pass filter with 577 nm was combined with the high-speed camera system to observe lanthanum vapour from lanthanum oxide. The band-pass filter for observation of lanthanum vapour includes line emission from lanthanum vapour and weak emissions from tungsten vapour. To discuss dynamic behaviour of lanthanum vapour, emission from tungsten and lanthanum vapour were compared.

Figure 7 shows representatives of high-speed snapshots of lanthanum vapour (a) and tungsten vapour (b) at 80 A. The indicated time in Fig. 7 (a), (b) corresponds to the

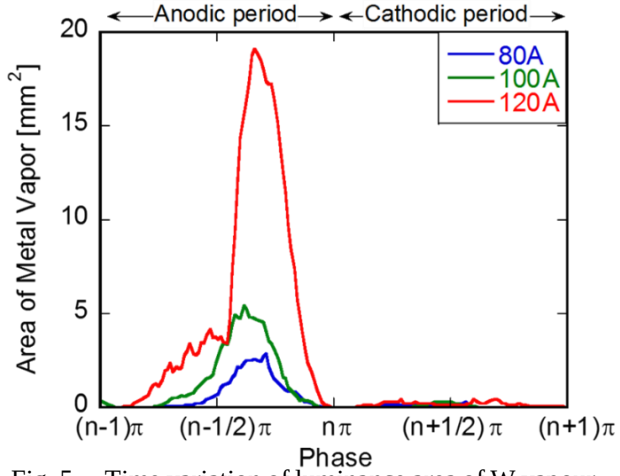

Fig. 5. Time variation of luminance area of W vapour during an AC cycle with different values of arc current.

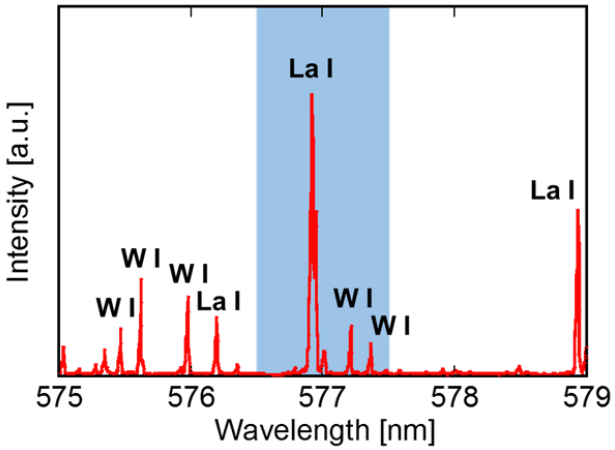

Fig. 6. Emission spectrum of multiphase arc in electrode region at centre wavelength of 577 nm.

waveform of arc current in Fig. 7 (c). The behaviour of emission at wavelength of 577 nm was different from that of tungsten vapour at wavelength of 393 nm. As shown in Fig. 7 (a), metal vapour observed at 3.0 ms during an AC cycle. In contrast, tungsten started to evaporate at 4.5 ms as shown in Fig. 7 (b). These results indicate that emission of lanthanum vapour from lanthanum oxide is successfully visualized. The observation of lanthanum vapour from tungsten electrode have never been reported because separation of the emission from tungsten and lanthanum vapour is difficult. In this study, the dynamic behaviour of lanthanum vapour was investigated by synchronized observation of tungsten and lanthanum vapour.

According to the synchronized observation, lanthanum oxide evaporated just before tungsten evaporation. These results suggest that evaporation of doped oxide triggers tungsten evaporation. First, the doped oxide evaporates before the tungsten evaporation at the anodic period because the boiling point of doped oxide is lower than that of tungsten. Vapour addition of metal from doped oxide into the arc leads to higher electrical conductivity. Consequently, heat flux from the arc to the electrode is enhanced after the evaporation of doped oxide, resulting in tungsten evaporation.

Based on the evaporation mechanism of tungsten-based electrode in the multiphase AC arc, reason for severer evaporation at higher arc current is discussed. Figure 8 shows representatives of high-speed snapshots of lanthanum vapour (a) and tungsten vapour (b) at 120 A. The indicated time in Fig. 8 (a), (b) corresponds to the waveform of arc current in Fig. 8 (c). At 120 A, lanthanum vapour and tungsten vapour observed at 1.0 ms and 2.5 ms, respectively. The evaporation timing of doped oxide at 120 A is earlier than that at 80 A as shown in Fig. 7 and 8 because higher arc current leads to higher electrode temperature. Therefore, tungsten started to evaporate before the peak top of arc current at higher arc current. Increase of the arc current before the peak top leads to higher electrode temperature, resulting in severer evaporation of tungsten.

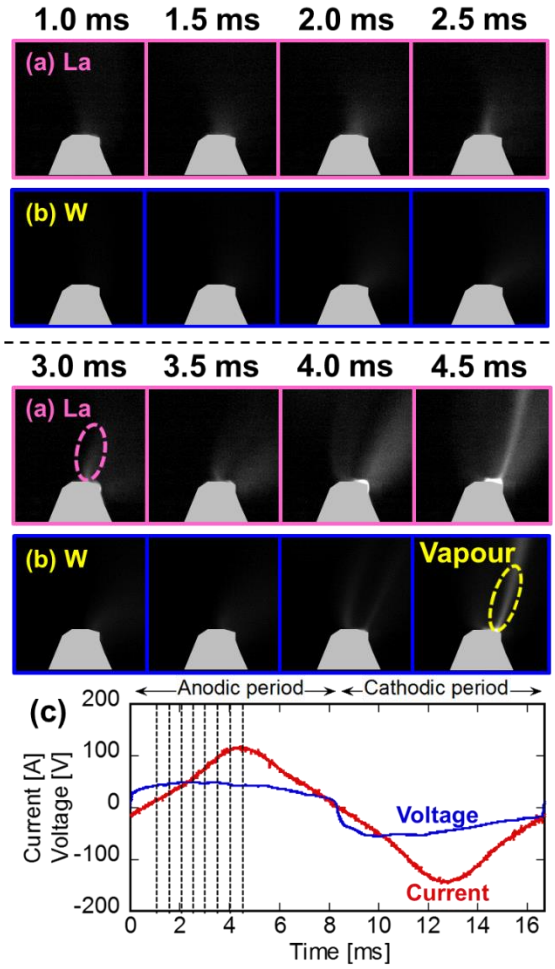

Fig. 7. High-speed snapshots of La vapour (a), W vapour (b) of La_2O_3-W at 80 A, and synchronized current/voltage waveforms (d).

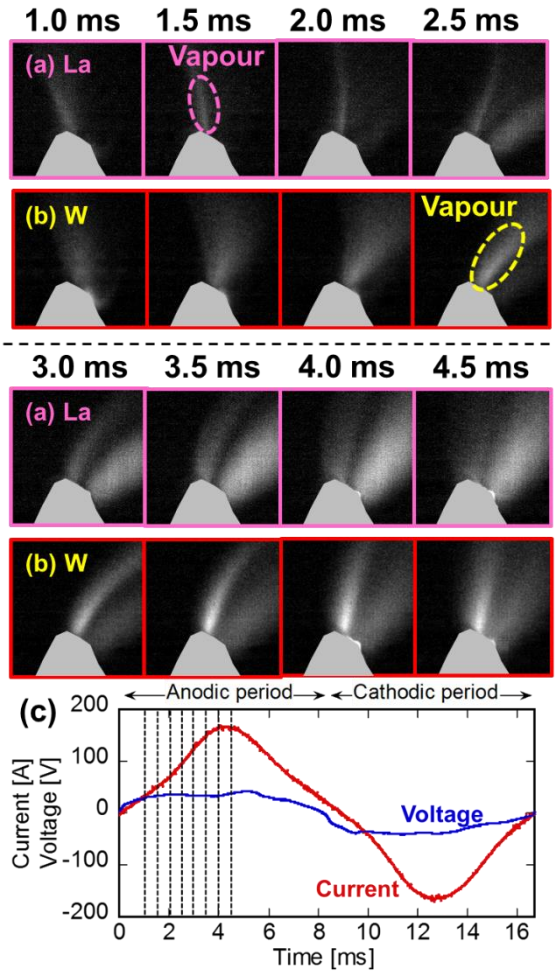

Fig. 8. High-speed snapshots of La vapour (a), W vapour (b) of La_2O_3-W at 120 A, and synchronized current/voltage waveforms (d).

4. Conclusion

The dynamic behaviour of metal vapour was successfully visualized by the high-speed camera observation combined with the appropriate band-pass filter system. Tungsten vapour and vapour from doped oxide were simultaneously observed with different values of arc current to investigate the evaporation mechanism of tungsten-based electrode in the multiphase AC arc. Obtained results revealed that the evaporation of doped oxide had an important role on the tungsten evaporation.

Tungsten evaporated just after the evaporation of doped oxide. Addition of metal vapour from doped oxide into the arc leads to the electrical conductivity, resulting in higher heat flux from the arc to the electrode. Therefore, evaporation of doped oxide triggers tungsten evaporation. At low arc current, tungsten starts to evaporate after the peak top of arc current, resulting in decreasing the tungsten evaporation rate. Understanding the erosion mechanism in more details enables us to realize the practical use of the multiphase AC arc in various applications.

5. References

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